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Cathanode Modulation System

R. J. ROCKWELL, FELLOW, IEEE

Abstract—**A system for high level, high efficiency amplitude modulation is described which avoids the use of a modulation transformer, thereby permitting the application of wideband feedback, resulting in very low distortion and a full power pass band of 20 to 20 000 Hz.**

PREVIOUS ART

IN REVIEWING past art prior to development of the "cathanode system," the major types of modulation circuits were investigated. Discussion of their relative characteristics follows.

Grid Modulation:[1] Probably the simplest type, is inherently nonlinear. Unmodulated anode efficiency in the order to 30 to 40 percent is typical, rising to only 45 to 60 percent at 100 percent modulation. Very good driver regulation or some type of regulation compensator is required to maintain constant excitation voltage during modulation. Likewise, the source of modulation must be capable of driving grid current without distorting the audio frequency wave shape. Considerable improvement may be had by operating the Class C grid modulated stage entirely below the point of grid current. This results in a parabolic output characteristic which, by proper matching with the opposite sign of the modulator tube, can produce quite low distortion. Low efficiency, however, still prevails with output power limited to approximately 25 percent of that available from the same tube operated Class C and anode modulated.

High Efficiency Grid Modulation:[1] A great improvement over the previously described circuit, achieves anode efficiencies in the order of 65 to 80 percent. This circuit requires more exact adjustment for satisfactory performance than some other types, such as anode modulation, but has the advantage of fewer high-power tubes. The linearity of this method of modulation is not particularly high, requiring a considerable amount of negative feedback to meet broadcast requirements.

High Efficiency Linear Amplifier:[1] Similar in characteristics to the high efficiency grid modulated circuit but somewhat poorer in efficiency in the order of 60 percent. negative feedback being necessary to reduce the relatively high inherent distortion.

High Efficiency Screen and Impedance Modulated Linear Amplifier: This circuit takes advantage of the high efficiency of the Class C amplifier, and produces high-level modulation in the final power amplifier. Large modulator tubes are not required. The tetrode carrier tube operates close to 80 percent efficiency and the tetrode peak tube approaches 80 percent at the peak of positive modulation. The net result is nearly 80 percent over the entire modulation cycle. Performance is superior to all other types discussed in this Section.

Suppressor Grid and Screen Grid Modulation:[1] Neither of these methods is widely used due to high inherent distortion and low anode efficiency. Since the appearance of the reference published in 1942, however, the characteristics of modern tetrodes have been greatly improved. Relatively low distortion with carrier efficiency between 35 and 40 percent and average modulation efficiency of 45 to 55 percent is now possible. These improvements have resulted in very acceptable commercially available equipment incorporating screen grid modulation up to 10 kW, higher power being limited by only 40 percent efficiency.

Cathode Modulation:[1] In which modulation voltage is applied between cathode and ground. This circuit combines the characteristics of both grid and anode modulation, exhibiting low efficiency only somewhat better than grid modulation.

Out-Phasing System:[1] Slightly used in this country until very recently. This method consists of two Class C amplifiers coupled to a common load. One method involves rotating the phase of these two amplifiers in opposite directions so that their individual outputs add or cancel. This results in nonlinear sinusoidal output, which can be somewhat corrected by partial amplitude modulation. Anode efficiency of the output stages can approach Class C efficiency at whatever phase position the stages are set when tuned. During modulation, however, the efficiency suffers, depending upon the amount of phase rotation. This system requires careful adjustment, not generally possible during program operation. Realization of acceptable distortion, RF carrier regulation, efficiency, etc., with the one setting of adjustments is apt to be difficult.

Anode Modulation:[1] Probably the most widely used circuit, capable of efficiencies in the order of 80 to 90 percent. This method is relatively simple to adjust, even while carrying program. It is inherently low in distortion and usually does not require overall negative feedback in order to meet broadcast requirements. Modulation power equal to one-half of the dc input power of the modulated stage is required, which involves tubes comparable in size to the Class C tube.

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The author is with the Crosley Broadcasting Corporation, Cincinnati, Ohio.

[1] F. E. Terman, *Radio Engineers' Handbook*. New York: McGraw-Hill, 1943, pp. 455–458, 533–546.

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CATHANODE MODULATION SYSTEM

Cathanode Modulation: Involves voltage excursions of both cathode an anode of the modulated RF output stage and the modulator stage; hence the name cathanode. This system incorporates the following features at 50 kW rating:

1) High level modulation with no modulation or interstage transformers,
2) Essentially flat audio system from 10 to 400 000 c/s prior to feedback shaping,
3) 100 percent modulated RF power from 20 to 20 000 c/s,
4) Distortion approximately 0.5 percent from 20 to 20 000 c/s,
5) Noise level greater than 60 dB below 100 percent modulation,
6) RF carrier regulation zero,
7) Final RF stage efficiency 90 percent,
8) Only three high power tubes used,
9) Idle modulator anode current only 400 mA per tube, and
10) All high voltage to ground excursions of modulated RF stage reduced to 50 percent of conventional high level anode modulated circuits.

Cathanode System Compared to Conventional High Level Modulation

Since the cathanode system is closest in circuitry to the conventional high level anode (plate) modulated circuit, the comparisons which will be made will be limited to the latter and at 50 kW output rating.

Figure 1 is a simplified circuit of the conventional high level anode modulated method. As seen, both the modulator stage and the modulated stage are connected to a common power supply of 10 kV.

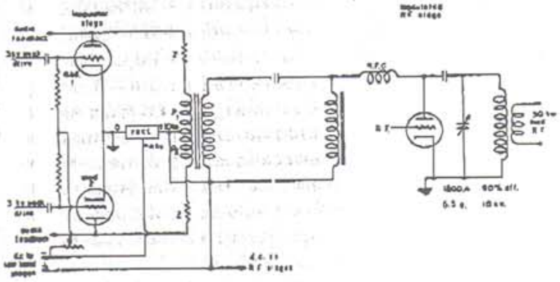

Fig. 1. Conventional high-level modulation circuit.

Since Class B modulator tubes produce only alternate negative excursions at their anodes, a modulation transformer is used to invert the excursion of one tube so as to produce positive modulation from one modulator and negative modulation from the other. That is, on one half cycle, the negative excursion of one modulator anode serves to increase the anode supply voltage of the modulated RF stage and on the next half cycle, the negative excursion of the other modulator anode serves to decrease the anode voltage of the modulated RF stage. Since the peak anode excursion available from either modulator tube is approximately 77 percent of the dc supply voltage, it follows that in order to obtain 100 percent modulation, the transformer must have a turns ratio S to P_1 or P_2 of 1.3 to 1.

$$10 \text{ kV} \times 0.77 \times 1.3 = 10 \text{ kV}.$$

At 50 kW output with an anode voltage of 10 kV, and an assumed efficiency of 90 percent, the Class C anode current will be 5.55 amperes.

$$\frac{50}{10\,000 \times 0.9} = 5.55.$$

At 5.55 amperes and 10 kV the resistance is 1800 Ω.

$$\frac{10\,000}{5.55} = 1800.$$

The 1800 Ω load of the modulated stage reflected through this transformer to each modulator will be 1065 Ω.

$$\frac{1800}{1.3^2} = 1065.$$

Since the peak transformer primary voltage, P_1 or P_2, will be 7.7 kV in order to produce the required peak secondary voltage of 10 kV, the primary peak current per tube or anode current will be 7.25 amperes plus 0.5 ampere static or 7.75 amperes.

$$\frac{7700}{1065} + 0.5 = 7.75.$$

The foregoing analysis assumes an idealized transformer. Actually, its winding resistance reduces the peak output voltage, making it necessary to increase the turn ratio slightly, which raises the modulator anode current by the square of this increase. The value of 7.75 peak amperes, therefore, can easily approach 8.0 amperes.

Since it is necessary to operate the modulator tubes in the Class B region in order to obtain reasonable efficiency and power, it follows that only one tube functions at a time. During the transition from one tube to the other, transformer primaries are likewise switched, resulting in switching transients due to the transformer leakage inductance. This form of distortion can be reduced by lower tube bias but at a large sacrifice in efficiency and output power. The usual compromise is a static modulator current of 0.5 to 0.75 ampere per tube, or a wasted power of 10 to 15 kw with objectionable switching transient distortion still prevailing. Negative feedback, as shown in Fig. 1, can be employed and can be very effective in reducing distortion and noise at the modulator output with some improvement at the transformer output. Since the transformer is balanced input and single output, there are inherent balanced and unbalanced capacities and leakage inductances within the windings which limit and unbalance the high-frequency response. At low frequencies, limitation is imposed by the shunt inductance. Phase rotation, therefore, occurs at both ends of the pass band and generally within this band. As a result, it is necessary to limit the feedback range near both ends of the pass band, resulting in rising distortion in the band near each end. In order to apply sufficient mid-range feedback and render it stable, it is usually necessary to isolate the transformer primary with series impedance (see Fig. 1). While these impedances greatly stablize feedback, they serve to decouple the primary from the tubes, thus leaving the transformer more free to insert distortion caused by its several nonlinear characteristics. Since it is desirable, and generally necessary to isolate the transformer in order to apply the required amount of feedback ahead of it, it follows then that it would be next to impossible to correct transformer difficulties by attempting to apply feedback at any point following the transformer. Therefore, it is quite obvious that elimination of the modulation transformer is highly desirable if high-fidelity transmission is desired.

Another form of distortion inherent in the circuit of Fig. 1 is brought about by radio frequency carrier-amplitude regulation (carrier shift). Assuming a distortionless modulator, carrier regulation distortion can be due to RF anode supply voltage variation caused by the varying modulator load, improper adjustment of the modulated RF amplifier, improper RF drive regulation, and insufficient peak emission in this stage. Since "a properly adjusted plate modulated Class C amplifier produces a modulation envelope that has very little distortion,"[1] there remains only the power supply regulation to be dealt with, assuming sufficient peak emission. Two helpful remedies are 1) separate anode voltage supply sources, so as to isolate the modulator load changes from affecting the RF amplifier anode voltage, or 2) some form of high speed voltage regulator which will maintain constant voltage at the RF stage. Recently designed equipment is now incorporating separate rectifiers, but lacks the improvements to be gained by eliminating the modulation transformer.

The circuit of Fig. 2 represents a simplified portion of the cathanode system using the same three high power tubes. It will be noted that the modulation transformer, which was effectively in series between the modulator and modulated stages of Fig. 1, has been replaced by two reactors which are effectively in parallel between these stages. These reactors may, if desired, be on one iron core, but must be of low capacity design so as to present a high-shunt impedance at all audio frequencies up to approximately 0.5 megacycle.[2] Sufficient inductance must also be provided so as to maintain sufficient shunt low-voltage impedance at approximately 5 Hz. These requirements, together with the high voltage-insulation requirement, dictate separate core design for high-power equipment.

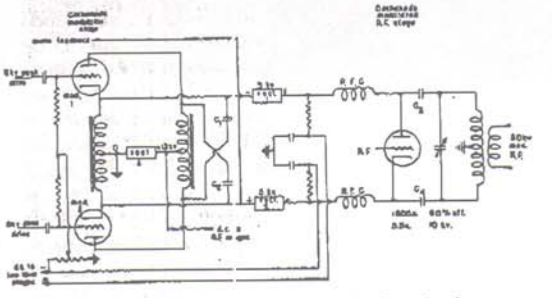

Fig. 2. Cathanode high-level modulation circuit.

Theory of Cathanode Modulator

It will be noted in Fig. 2 that the cathode of modulator tube 1 connects directly through rectifier 1 to the modulated RF stage anode. It will also be noted that the anode of modulator tube 1 connects through C_3 and rectifier 2 to the modulated RF cathode. The action is similar to that of a phase splitter, in that equal and opposite ac excursions occur, positive at the cathode and negative at the anode, as the grid is driven in the positive direction. The negative grid excursion serves to cut off the slight static anode current and keeps it cut off while tube 2 functions. As stated earlier in discussing Fig. 1, the peak cathode–anode excursion is approximately 77 percent of the applied dc voltage. The circuit of Fig. 2 is no different in that respect, except that this excursion is divided into two equal excursions, one at the cathode, the other at the anode, each excursion approximating 38.5 percent of the dc voltage. Since no modulation transformer is used, its 1.3 V step-up ratio is lost. It is, therefore, necessary to increase the dc voltage supplying the modulator by a factor of 1.3 to 13 kV in order to obtain 100 percent modulation.

Referring again to the phase splitter action of modulator tube 1, the positive cathode excursion will be 38.5 percent of 13 kV or a peak voltage of 5 kV. This

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[1] F. E. Terman, *Radio Engineers' Handbook*. New York: McGraw-Hill, 1943, p. 226.

adds to the 5 kV of rectifier 1, producing a positive 10 kV peak voltage at the modulated RF anode. Likewise, the 5 kV negative peak anode excursion adds through capacitor C_2 to the 5 kV of rectifier 2, producing a negative 10 kV peak voltage at the cathode of the modulated RF stage. The unmodulated RF stage supply voltage consisting of the two 5 kV rectifiers in series or 10 kV, is therefore increased to 20 kV on positive peaks producing a positive modulation of 100 percent. The action of modulator tube 2 is precisely the same as 1, except that the voltage additions become subtractions, thus resulting in a peak cathode–anode voltage at the RF stage of zero or a negative modulation of 100 percent.

dc Voltage to Ground

Therefore, it is seen that the modulated RF stage anode reaches a positive peak voltage of 10 kV to ground and its cathode, a negative peak voltage of 10 kV to ground (20 kV peak anode to cathode during positive modulation). In the circuit of Fig. 1, the cathode is grounded, but the anode reaches 20 kV to ground. The cathanode circuit, therefore, reduces flashover voltage to ground by 50 percent, thus greatly reducing one of the serious problems in high power, high-level modulated transmitters. dc plus RF voltage to ground may be determined by multiplying dc values by approximately 1.8.

Reduced Plate Current

In discussing the conventional high-level modulated circuit at 50 kW rating, it was shown that the instantaneous modulator peak anode current, at 100 percent modulation, was approximately 8.0 amperes due to the low reflected load of approximately 1065 Ω. In the cathanode circuit, the modulator stage couples directly to the Class C RF load which approximates 1800 Ω. As a result, the instantaneous modulator peak anode current is only 5.5 amperes. Thus the modulator tubes can be reduced in size, since their anode current requirement is approximately 70 percent of that required in the conventional circuit. The new Federal Type F-6921 tubes, which are considerably smaller than the Federal Type 9C28, are now used in the cathanode modulator.

Modulator Generator Impedance

The modulator tubes now used in the cathanode system, Federal Type 6921, have an optimum load rating of approximately 1870 Ω anode to anode, or 468 Ω per tube. The previously mentioned reflected cathanode load of approximately 1800 Ω, therefore, results in a much lower ratio of generator impedance to load, nearly twice the ratio of the conventional 1060 Ω transformer coupled circuit.

SCALE MODEL MODULATOR TESTS

Modulator Characteristics

Since the cathanode modulator and its associated circuitry is the heart of the cathanode system, considerable time was spent in investigating its characteristics prior to full scale design and construction.

TABLE I

	Federal 6921 (values for two tubes)	West. Elec. 300-B (values for two tubes)
Anode Voltage	13 000 V	400 V
Maximum Anode Current per tube	10 A	100 mA
Bias Voltage (near I_p cutoff)	3000 V	100 V
Grid Current	0 mA	0 mA
Amplification Constant	4.25	4.0
Anode to Anode Load-Class "B"	1870 Ω	2000 Ω (measured)
Anode Dissipation per tube 6921	30 kW	40 W

In order to facilitate investigation of the cathanode circuit prior to construction, a low-power modulator stage was set up using Western Electric Type 300B tubes since they were quite close in characteristics to the Federal Type 6921 tubes to be used in the 50 kW transmitter. Table I compares the two tube types.

It will be noted that the two following anode current-anode voltage versus grid voltage curves, Figs. 3 and 4, indicate similar characteristics for F6921 and W.E. 300B, from which it was concluded that the performance of 300B tubes in various circuit arrangements would be fairly indicative of F6921 performance. Effective μ, for instance, from these curves, is 3.05 between -1600 and -2000 V bias for F6921, and 3.05 between -40 and -60 V bias for 300B.

Figure 5 shows the generator impedance of two type 300B Western Electric tubes in anode, cathode, and cathanode output circuits. It will be noted that anode output and, to some extent, cathode output, do not maintain constant generator impedance. Of great importance is the fact that the generator impedance for cathanode output is less than one half that of cathode output and approximately one tenth that of anode output. This extremely low impedance is required to produce wideband response with the low reactance load at high frequencies.

Figure 6 shows the power output of the same three circuits. Note that extrapolation of the cathanode curve past tube rating results in more output than either cathode or anode output. This advantage, of course, can be realized with larger tubes.

Figures 7, 8, and 9 are the circuits used to obtain the data for Figs. 5 and 6. Operating conditions were: Anode Voltage, 400 V dc; Bias Voltage, 160 V dc almost at anode current cutoff; Grid Drive, just below grid current.

In Fig. 9, each tube alternately acts as a half cycle phase splitter, developing half its output across half of the cathode reactor and the other half of its output across half of the anode reactor. Each tube, therefore, develops its full output directly across the load.

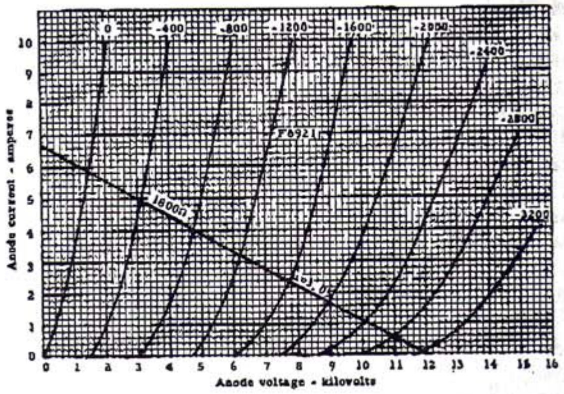

Fig. 3. Anode characteristics ITT type F6921 power triode.

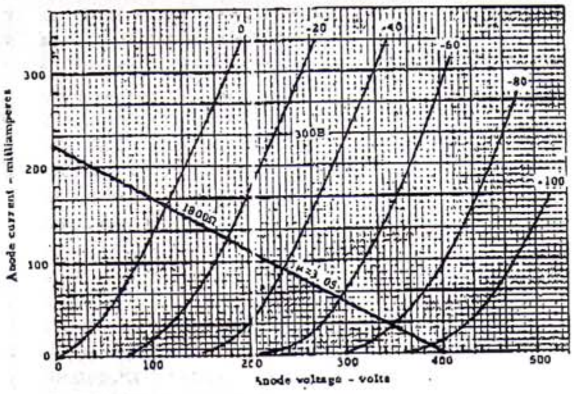

Fig. 4. Anode characteristics W.E. type 300B power triode.

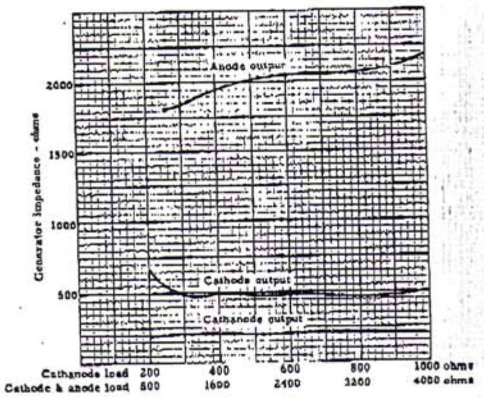

Fig. 5. Generator impedance vs. load for type W.E. 300B tube.

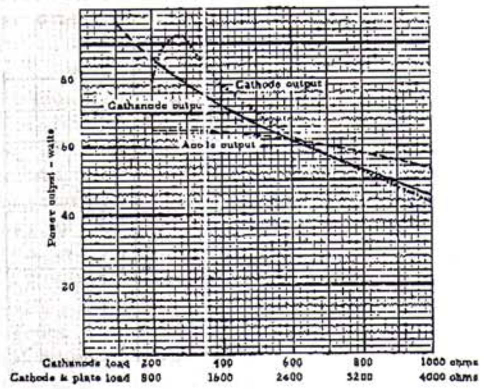

Fig. 6. Power output vs. load for type W.E. 300B tubes.

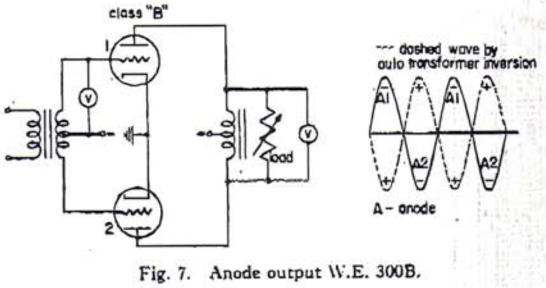

Fig. 7. Anode output W.E. 300B.

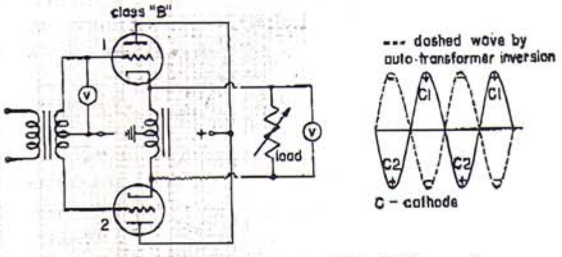

Fig. 8. Cathode output W.E. 300B.

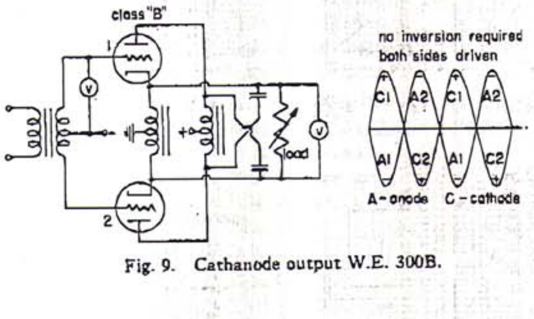

Fig. 9. Cathanode output W.E. 300B.

Scale Model Conclusions

It is seen from Figs. 5 and 6 that the cathanode circuit offers the ultimate in performance as follows:

1) Almost ten to one reduction in generator impedance, 2) Constant generator impedance, and 3) Maximum power.

These characteristics are of great importance in driving the Class C load whose impedance falls rapidly at high frequency mainly due to the reactance of the anode coupling capacitors. See Fig. 10, Curve 2.

Floating Drive Stages

In the conventional connection of Fig. 1, a peak positive grid excursion of 3 kV to ground (cathode grounded) would be required for full drive. In the cathanode connection of Fig. 2, it is seen that the same requirement exists between grid and cathode, but since the cathode rises to a positive 5 kV peak, the grid to ground excursion is therefore 3 kV+5 kV or 8 kV. This 8 kV peak modulator grid excursion, which of course is 16 kV peak to peak, can be accomplished in the conventional manner as shown in Fig. 11.

It will be noted, however, that a positive dc supply voltage of approximately 21 kV would be required for the amplifier producing this excursion:

$$\frac{16}{0.77} = 20.8 \text{ kV}.$$

The 30 kΩ anode resistors of this stage could be replaced by a center tapped reactor, thus requiring positive dc voltage no higher than the 13 kV modulator supply. Using a reactor, however, greatly complicates the feedback requirements, due to added phase rotation. In either case, a high-power stage would be required.

Since the actual required grid to cathode peak excursion of the modulator is only approximately 3 kV, it is possible to "float" the drive stage as shown in Fig. 12. It will be seen in Fig. 12 that the modulator drive stage cathode is returned to the modulator cathode, thus only requiring approximately a 3 kV peak drive excursion (6 kV peak to peak) instead of 8 kV (16 kV peak to peak).

From Fig. 12 it can be seen that the 13 kV anode supply voltage of the 750 TL stage and the cathode of this tube are both carried in a positive direction along with the associated modulator tube grid. This is the result of a negative excursion of the 750 TL grid with respect to its cathode. Any impedance directly from this grid to ground, therefore, will cause a greater excursion grid to cathode when the 750 TL anode supply voltage and its cathode experience the positive excursion. This condition is therefore regenerative representing positive feedback. If the impedance is not sufficiently high, oscillation will result.

Conversely, the phase reversal in the 845 stage results in degeneration from impedance grid to ground. It can therefore be conventionally driven grid to ground, thus inserting advantageous degeneration or negative feedback. This degeneration is made adjustable by the potentiometer between the 845 cathode resistors and ground for use in balancing the 845 tubes.

The 845 stage is partially floating since its cathode only receives approximately 9.7 percent of the modulator cathode excursion.

$$\frac{1500\,\Omega}{1500 + 14\,000\,\Omega} \times 100 = 9.7 \text{ percent}.$$

Since the grids of the 845 stage are driven in a conventional manner, negative feedback is inherently introduced at this stage. This arises from the fact that a positive 845 grid excursion causes the modulator cathode to swing positive. Nine and seven-tenths percent (9.7 percent) of this cathode excursion is applied to the 845 cathode. Since the 845 anode supply is tightly coupled to the modulator cathode by C_1 or C_2, it also receives a positive excursion. Thus, during the 845 positive grid excursion, both the 845 anode and cathode receive a positive excursion which is degenerative.

By changing the 9.7 percent insertion, the 845, 750 TL, and 6921 stages can be shifted from degeneration to regeneration. Nine and seven-tenths percent (9.7 percent) results in a slight regenerative peaking of the wave which compensates for slight flattening in the modulated RF stage.

Feedback Loops

Only audio feedback is required for fairly satisfactory distortion. A value of 0.8 percent was measured with a feedback value of 21 dB.

Noise, primarily 120 c, originating in the ac filament of the 50 kW RF stage, does not appear across the dc supply to the stage, and is therefore not fed back for reduction. Insertion of hum bucking at the transmitter input reduced overall noise to more than 60 dB below 100 percent modulation.

After approximately six months operation, however, distortion slowly increased to approximately 2 percent. Investigation revealed that the cause was normal aging of the 50 kW RF tube, resulting in slight nonlinearity. Since the tube was still perfectly useable for many thousand additional hours, it was determined that overall RF feedback should be added to reduce distortion on aged tubes as well as reduce overall noise.

The conventional method of applying rectified RF feedback and audio feedback is, of course, to insert the RF feedback ahead of the point of audio feedback insertion. It is mandatory that the opened audio-feedback loop have the required response characteristic several octaves above and below the pass band in order to maintain gain and phase safety factors. With this loop closed,

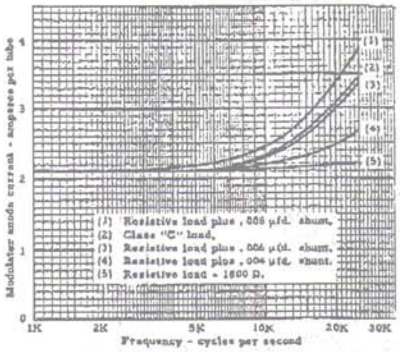

Fig. 10. Cathanode modulator load tests at 90 percent modulation equivalent.

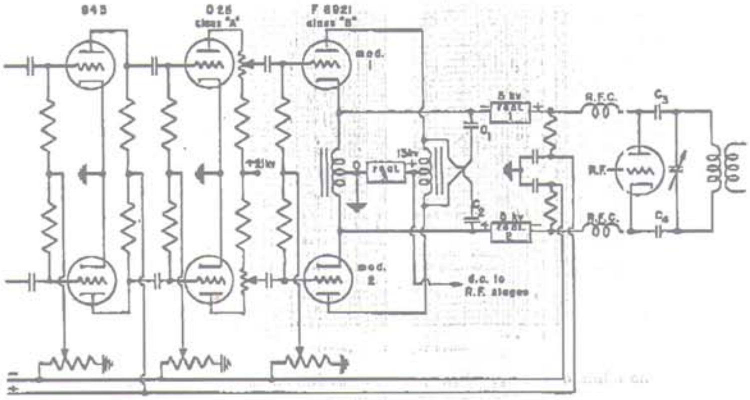

Fig. 11. Cathanode circuit with conventional drive stages.

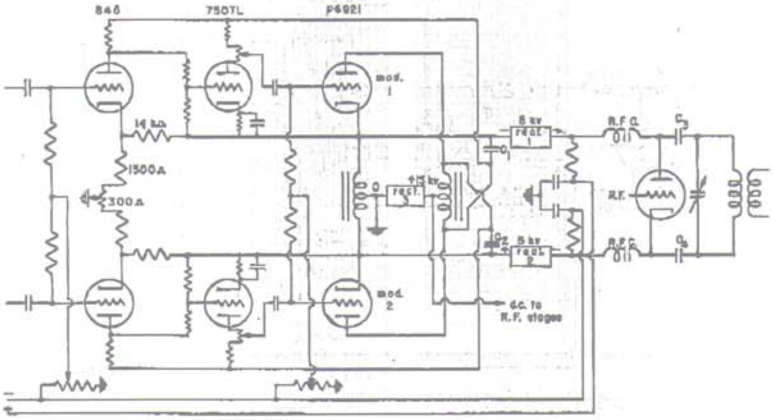

Fig. 12. Cathanode system with floating drive stages.

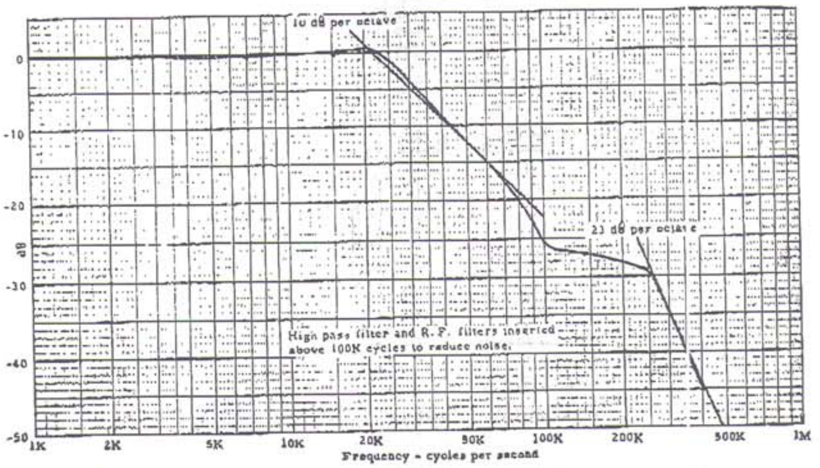

Fig. 13. Open loop combined rectified RF and AF feedback characteristic.

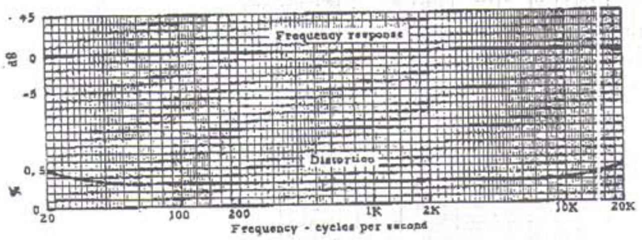

Fig. 14. Response characteristics.

the opened rectified RF feedback loop must also be similarly shaped so as to provide the same conditions relative to the audio-feedback loop which it surrounds. These multiple requirements are greatly simplified by combining RF and audio-feedback loops. See Fig. 15(b). Figure 13 is a plot of the high-frequency response to 400 000 c of the combined AF and rectified RF opened loop. This curve is in good agreement with the required characteristic.[3]

Figure 14 represents the nominal frequency response and distortion averaged from several sets of data taken at intervals through a period of several weeks.

SPECIAL CIRCUITRY

Electric A F Balance Servo

From Figs. 2 and 15, it is obvious that the "cathanode system" is inherently a balanced circuit. In fact, the exceptionally low distortion realized depends upon maintaining accurate voltage balance from modulator anodes or cathodes to ground, equal total AF gain from the 6SN7 stage through the 6921 modulator stages, as well as equal individual stage gain.

In order to develop balanced voltages from modulator cathodes to ground, it is essential that all "paired" impedances throughout the system be equal, particularly impedances directly or indirectly to ground.

Since the two 5 kV floating rectifiers which supply the 50 kW RF stage are also used for modulator bias, low voltage supplies, etc., it was necessary to maintain equal ac impedance at the unequal plus and minus dc dividing networks. This requirement was met by adding a balancing resistor of 23 kΩ from one modulator cathode to ground. A tap 375 Ω from ground on this resistor provides a convenient voltage source for high frequency AF feedback [see Fig. 15(b)].

Of importance in understanding the functioning of this circuit is the fact that the modulator tubes are actually operating as Class B phase splitters. The balanced cathode to ground or anode to ground voltage requirement, therefore is, at any instant, a balance of anode and cathode excursion of one modulator tube to

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[3] F. E. Terman, *Radio Engineers' Handbook.* New York: McGraw-Hill, 1943, p. 223.

ground [see Fig. 15(b)]. A convenient balance measuring technique involves connecting two matched 20 kΩ 200 watt resistors in series across the modulator output and measuring audio voltage from the center of these resistors to ground. Approximately 15 to 30 volts should appear at 80 percent modulation at mid-range frequencies, e.g., 1000 c. This balance will obtain, even though the two modulator tubes are driven unequally, exhibiting unequal cathode currents and producing unequal plus and minus modulated RF output.

However, if the balanced circuit is intentionally unbalanced by loading either modulator cathode with approximately 25 kΩ to ground, the resulting unbalance will increase the 15 to 30 volts mentioned above and will dengerate one 845 cathode and regenerate the other, resulting in unbalance of previously balanced modulator grid drive and, of course, causing unbalanced RF modulation and increased distortion.

In order to insure balanced operation, the modulator cathode to cathode voltage is sampled through two 150 kΩ resistors and the voltage unbalance injected through two 2 μF coupling condensers and a 1 kΩ potentiometer P_3 into the anode supply of the 6SN7 stage [see Figs. 15(a) and (b)].

This electronic servo can be set to either regenerate or degenerate an intentional unbalance. The correct setting is the position of P_3 which produces no change in modulator anode current balance when the circuit is intentionally unbalanced by connecting the 25 k resistor from either modulator cathode to ground.

Bias Stabilization

Referring to Fig. 15(b), it will be noted that a series of four 1N2071 silicon diodes shunted with a 10 kΩ rheostat are connected in series with the 50 kΩ grid resistor of the top positive modulator tube. These diodes serve to short out the rheostat during negative grid excursions, thus making the grid resistance lower for negative excursions than for positive. This action results in a cumulative change in charge across the 3 μF bias filter condenser and the grid coupling condenser, thus compensating for the fact that the voltage drop across the cathode reactor, during signal, increases the grid to cathode bias of the top (positive) modulator tube, but not the bottom (negative) tube since the bias rectifier 2 connects directly to the bottom cathode. Without this circuit, the indicated bias on the top modulator grid increases approximately 100 volts with 100 percent modulation which shifts bias on the top modulator tube, thus slightly increasing distortion.

Figure 15(b) also shows the grid bias voltmeters connected to the modulator grids rather than to the bias supply to each tube. This makes it possible to read a bias shift at the grids in the event of grid leakage or emission within the tube during modulation. These meters should not indicate a bias change at any percentage of tone modulation with good modulator tubes. Loss of bias and abnormally high modulator-plate current with tone may indicate contaminated grids.

NEUTRALIZING TRANSFORMER

Figure 15(b) shows the neutralizing transformer T_2, the purpose of which is to provide a small amount of regenerative voltage from modulator output to modulator grids to compensate for the inherent degeneration due to grid-anode capacity within the modulator tubes. Without this transformer, modulation at 10 kHz is limited to approximately 90 percent, due to the input reactance of the modulator tubes which is approximately expressed by:

$$\text{input capacity} = (1 + \mu) \text{ anode to grid capacity.}$$

This transformer is, of course, unnecessary with a lower impedance, higher power drive stage. By simply reducing the 30 kΩ anode resistors of this 750 TL stage, 100 percent modulation is achieved. This, of course, wastes power and requires larger drive tubes. Previous discussions relative to floating the drive stage (see Fig. 12) described the method for using tubes of much smaller size. These air cooled 750 TL tubes operating within rating with the neutralizing transformer produce 100 percent modulation at 20 kc. Since only high frequencies are involved, the transformer was designed to operate from 6 to 20 kHz and, as seen in Fig. 15(b), circuitry is incorporated to isolate it below 6 kHz.

TRIFILAR RF OUTPUT INDUCTANCE

Figure 15(c) is a physical circuit of the trifilar RF output inductance. It will be noted that the copper tubing coil has a tightly coupled bifilar winding actually taped turn for turn to the copper coil. This coupled winding consists of #14 flexible wire insulated for 60 kv. Since the copper coil is grounded at the center, the RF voltage at this point is zero; therefore, the RF voltage at the center terminals of the trifilar coil will be essentially zero. These terminals connect directly to rectifiers 1 and 2; there will, therefore, be a modulated peak dc voltage across them which varies from 0 to 20 kV. Hence, it can be seen that essentially no RF voltage is fed back to the modulation stage. This made it possible to dispense with the usual RF chokes shown in Fig. 2 which series resonated with the coupling condensers C_3 and C_4 causing a serious dip in response at 70 kHz. For complete RF isolation, very small 125 μH chokes were used which moved the resonance to 130 kHz where the dip, damped by resistors shunting the chokes, was utilized to shape the beginning of the high-frequency feedback step. A second trifilar winding of only a few turns was added to sample the modulated RF voltage for rectified RF feedback. The very tight coupling afforded by this winding keeps phase rotation at a minimum and permitted grounding the center of the feedback winding near the audio input stage, thus eliminating ground drop voltage insertion into the feedback loop.

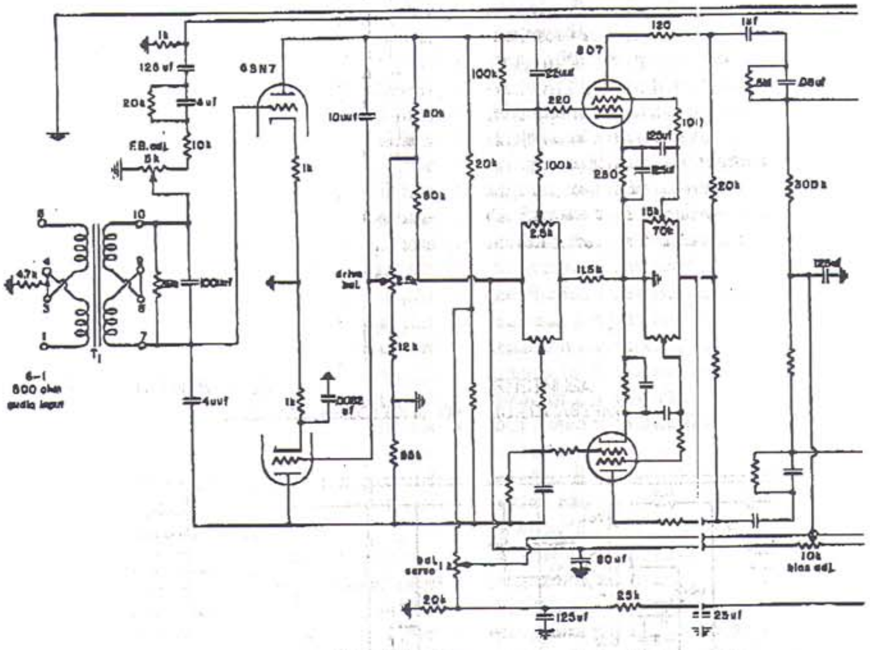

Fig. 15(a). Input stages.

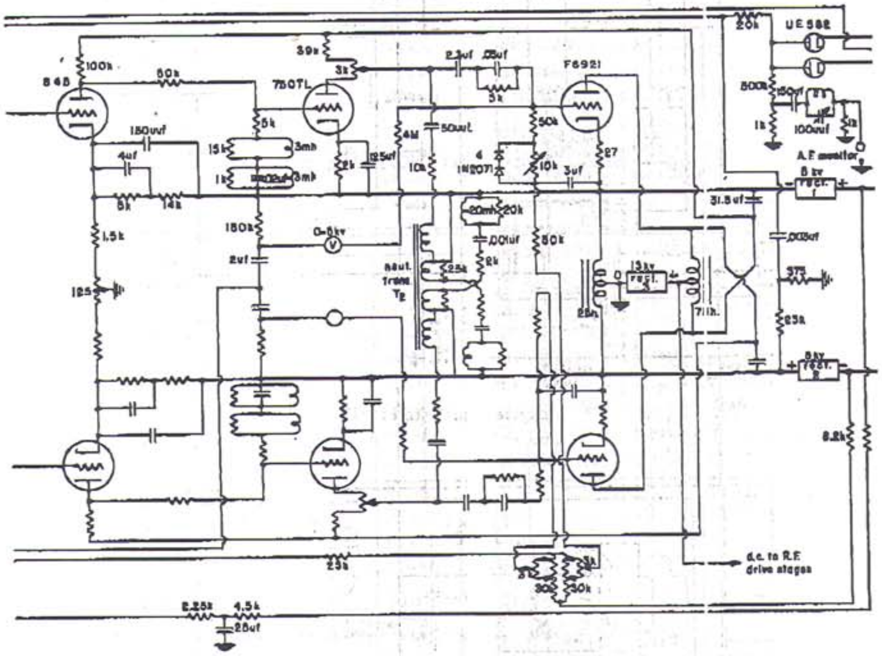

Fig. 15(b). Cathanode modulator, floating drive stages and RF feedback rectifier.

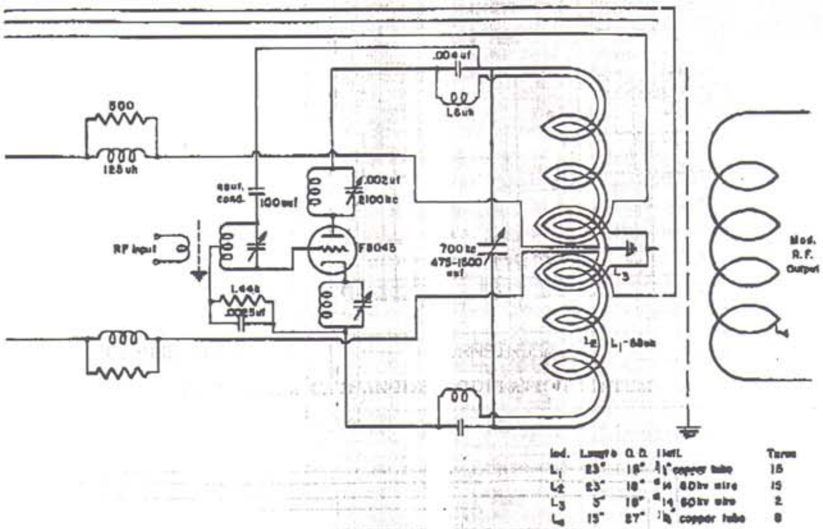

Fig. 15(c). Trifilar RF output inductance and 50 kW cathanode modulated RF stage.

Rectifiers

There are only two power rectifiers in the cathanode transmitter. The split dual 5 kV rectifier designated 1 and 2 and the 13 kV rectifier designated 3 in Fig. 15(b).

The floating rectifiers 1 and 2 are essentially one full-wave, three-phase, six-element rectifier. The circuit is divided as seen in Fig. 16, into two three-element isolated sections so as to provide a 5 kV unit in series with each modulator output. Electrically, each of the three rectifier power transformers has two separate secondary windings instead of one. Each three-element section produces a 180 Hz ripple; however, since the two sections are opposite in polarity, the ripple voltage of the two sections are 60° apart in phase, thus producing a 360 Hz ripple at the modulated RF stage load. Since the power transformer secondaries exhibit approximately 0.02 μF to ground, special precautions were taken to prevent shunting the wide band modulator. The filter reactor for each rectifier was split into two reactors, thus isolating the transformer secondaries and rectifier elements with reactance. Series resonance at 2 kHz was avoided by damping the circuit with 20 kΩ across the transformer capacity to ground. A 0.1 μF capacitor in series with the 20 kΩ resistor serves to block dc.

The modulator rectifier is a standard 13 kV full wave, three-phase, six-element configuration. The only special feature is use of a very low inductance filter reactor of only one-quarter henry followed by a 30 μF capacitor in order to suppress voltage bounce during modulation.

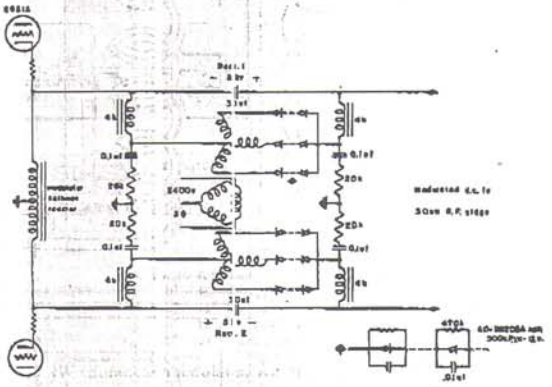

Fig. 16. Split floating rectifiers.

Listening Test

Performance measurements of the cathanode transmitter described definitely excelled predictions in all categories. It was determined, for example, that distortion could be held to approximately 0.25 percent over the range of 100 to 10 000 c/s, approximately one-tenth that of commercially available equipment, and to approximately 0.3 percent over a wider range (see Fig. 14). Since instantaneous (0.5 second) switching facilities were incorporated, fast A–B comparison with the alternate 50 kW conventional high level modulated transmitter were made. It was also possible to switch high fidelity monitoring speakers from one demodulator to the other with both transmitters operating; one into the antenna, the other into a resistive load. Prior to these tests, the conventional transmitter measured approximately 2.0 percent distortion, and flat within ±1 dB from 50 to 10 000 Hz.

During the listening tests, the following determinations were made relative to the new transmitter.

TABLE II

Program Material	Observation
Orchestral	Cleaner, crisper; individual instruments stand out
Speech	More presence, crisper
Piano	Definitely superior on attack, clean base

The new transmitter was used for several weeks prior to making any announcements concerning new equipment. During this time numerous complimentary letters were received commenting favorably on the improved fidelity.

Thus, it appears that measurements and listening tests are both verified by unsolicited listener reaction. It is apparent that the public can and does appreciate high-fidelity transmission.

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The vertical radiator was put into service in June, 1933, and a quantity of data was obtained on the comparison of this antenna with the conventional T antenna that had been in use at WLW for many years. The T antenna was of the conventional type, supported by two 300-foot towers. It operated at approximately 0.75 of its fundamental wavelength. By leaving the T antenna installed and by arranging to switch the 50-kilowat transmitter from it to the vertical antenna, there was afforded the opportunity of getting absolute comparisons between them at all times of the day and under various conditions. Absolute field strength measurements were taken with calibrated instruments and several recording instruments were used to record fading. So far as is known, this is the first case where absolute comparisons could be made between the two types of antennas, with all other conditions, including power, frequency, location, and radiation, remaining the same. The measured results agree with the calculated prediction within the limits of measurements. (See Fig. 15.)

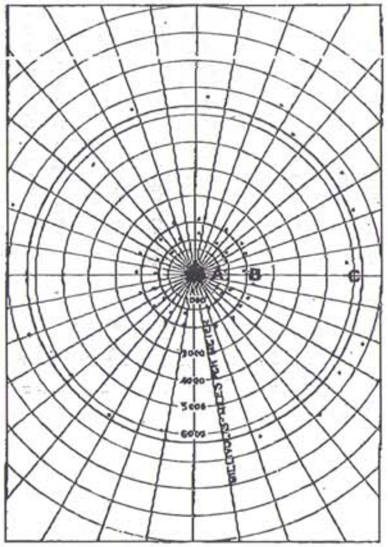

Fig. 16—Relative field intensities, quarter-wave antenna and vertical power.
Curve A: Field intensity, 50-kilowatt input to quarter-wave antenna.
Curve B: Field intensity, 50-kilowatt input to 0.58-wave antenna.
Curve C: Field intensity, 500-kilowatt input to 0.58-wave antenna.

Fig. 16 shows field strength contours for the two antennas. Assuming that receivers without automatic volume control produce satisfactory signals when the fading does not exceed six decibels, and assuming that receivers with automatic volume control produce satisfactory signals when the fading does not exceed twenty decibels, it is found that the area of nonfading service for the first type receiver was increased 66 per cent by the vertical radiator, and the nonfading area for the second type of receiver was increased 186 per cent. Both of these increases are due to the antenna alone as they are derived from measurements based on 50-kilowatt power. The average increase of field intensity in the secondary coverage area, based on hundreds of measurements, was 39 per cent. Thus the vertical radiator produces an increase of field strength equivalent to doubling the transmitter power, in the case of WLW. This would not necessarily be true at other locations since the efficiency of the vertical type radiator, both with regard to its intensification of the ground wave as well as to its reduction of sky wave, depends considerably upon the electrical properties of the immediately adjacent earth.

PERFORMANCE

The first equipment arrived on the field approximately July 1, 1933, and on November 1st of that year 500 kilowatts were put on the air. Within a few days this power was increased to well over 500 kilowatts with 100 per cent modulation. No change of major importance or appreciable expense was found necessary in the design. The installation progressed in accordance with a schedule formed many months before, an achievement all too rare in broadcast installation history. A brief summary of the tests is given below to indicate the general performance of the equipment under typical operating conditions.

The normal power output is 525 kilowatts. The normal power input to the 500-kilowatt amplifier including all auxiliary apparatus, but excluding the 50-kilowatt exciter, is 1150 kilowatts for zero modulation, 1600 kilowatts for 100 per cent sinusoidal modulation, and 1225 kilowatts for normal average modulation. The level of the residual carrier hum is 66 decibels below the level corresponding to 100 per cent modulation.

The over-all audio harmonics present in the modulation envelope increase from zero at zero percent modulation to 5.3 percent root-mean-square at 95 per cent modulation. The variation of audio harmonics with the per cent modulation is shown in Fig. 17. The reference frequency was 200 cycles. At lower frequencies the harmonic content is practically unchanged; at higher frequencies it is lower than indicated